

Electroweak Physics: Status and Outlook

(Selective Topics)

Outline

1. Overview
2. Precision Electroweak Studies (In Search of "New Physics")
 - i) 10 yrs of Top Physics: $(m_t - m_W)$ connection
 - ii) Higgs Mass
 - iii) Harbingers of Supersymmetry ($g_{\mu-2}$)
 - iv) Atomic P.V. & $e\bar{e}$ Scattering E158: $Z', Z^* \dots$
3. Flavor Mixing
 - i) CKM Unitarity
 - ii) Lepton Mixing & CP Violation (Doable) (DUSEL)
4. Outlook

1. Overview

"We are the symmetries of Nature"

<u>General Coord. Inv</u>	+	$SU(3)_c \times SU(2)_L \times U(1)_Y$	+	Higgs Mechanism
<u>Gravity</u>		<u>QCD</u>		<u>Electroweak</u>
<u>Supergravity</u>		Perfect theory!		> 24 Parameters
<u>Superstrings</u>		No Parameters		EWSB $v = 250 \text{ GeV}$

Potential For "New Physics"
~ 1 TeV

Extended Higgs Sector
More Fermions
Z', W' Bosons...

- * Supersymmetry
- * Extra Dimensions
- Strong Dynamics

The Search For "New Physics"

i) High Energy Colliders (Most Direct) explore Multi-TeV

Tevatron (2 TeV) → LHC (14 TeV $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)

ILC (~1 TeV e^+e^-)

Find Higgs Scalar, SUSY, Extra Dimensions... **Black Holes etc.**

or Bust

ii) Rare or Forbidden Processes Explore TeV $\rightarrow 10^{16}$ GeV!

* Neutrino Oscillations $m_\nu \sim m_\nu^2/M$ (Big Winner)

$\mu \rightarrow e \gamma$ (10^{-13}), $\mu N \rightarrow e N$ (10^{-17}), $\tau \rightarrow \mu \gamma$ (10^{-8}) ...

Electric Dipole Moments: $e, n, D, p, \mu \dots$ Atoms, Molecules

$K \rightarrow \pi \nu \bar{\nu}$, $K_L \rightarrow \mu e$, $B \rightarrow \mu \bar{\mu}$, $b \rightarrow s \gamma \dots B_s \rightarrow \bar{B}_s \dots$

$p \rightarrow e^+ \pi^0$, $p \rightarrow K^+ \bar{\nu} \dots M_X \approx 10^{16}$ GeV $\tau_p \approx 10^{35}$ yr

$n \rightarrow \bar{n}$ osc., Neutrinoless Double Beta Decay etc.

Endangered Species in the USA.

Fortunately, the rest of the world is safe. { CERN, Japan

iii) Precision Studies: Explore Quantum Loops ($\pm 1\% \rightarrow \pm 0.1\%$)

Sensitive to Multi-TeV Physics (Indirect)

Also, advance theory + exp. technique! Exciting Confrontation

Examples: $\alpha, G_\mu, m_Z, m_W, \sin^2 \theta_W, m_t \rightarrow m_{Higgs}, S, T, Susy$

- g_μ^2
- Atomic P.V., $\nu_\mu N$, pol.ee, ep
- CKM Unitarity
- ⋮

2.) Precision Electroweak Studies

Powerful Constraint on "New Physics"

And Beautiful Confirmation of Standard Model

eg Erler + LARGACKER (#2004 PDG Global Fit)

$$\underline{m_H = 113_{-40}^{+56} \text{ GeV}}, \quad m_H < 241 \text{ GeV (95\% CL)}$$

Exp $m_H > 114.4 \text{ GeV}$

Light Higgs Favored! (SUSY)

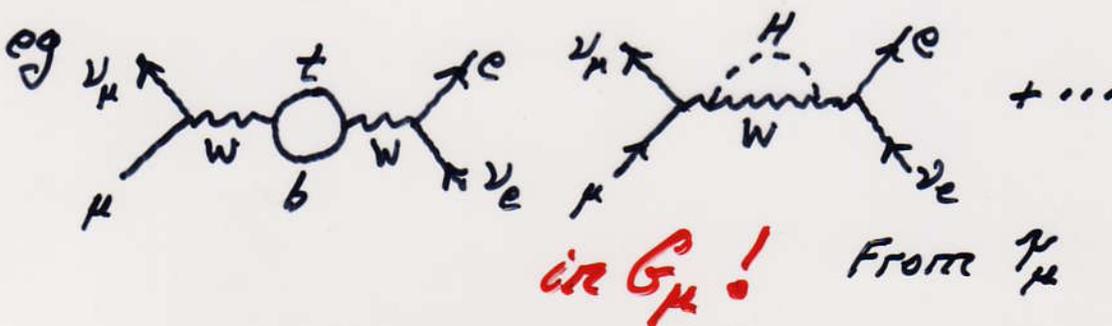
No Evidence For Strong Dynamics (Technicolor)

Stem From: $\frac{e_0^2}{g_{2_0}^2} = 1 - (m_W^0/m_Z^0)^2 = \sin^2 \theta_W^0$ **Natural Rel. Custodial Sym.**

So: $\Delta\Gamma(m_Z, m_H, \text{new phys}) = 1 - \frac{\pi\alpha}{\sqrt{2}G_\mu m_Z^2 (1 - m_W^2/m_Z^2)}$

$$\hat{\Delta}\Gamma(m_Z, m_H, \text{new phys}) = 1 - \frac{2\sqrt{2}\pi\alpha}{G_\mu m_Z^2 \sin^2 2\theta_W(m_Z) \overline{NS}}$$

Radiative Corrections (several %)



$\alpha = \frac{1}{137.03599890(50)}$ from g_{e^2} (new exp \rightarrow 15x better)

$G_\mu = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$ from Γ_μ (new exp \rightarrow 20x better)

$m_t = 91.1875(21) \text{ GeV}$

Together with $m_W + \sin^2 \theta_W \rightarrow m_t \sim 160-180 \text{ GeV}$ in 1990's (suggestive)

* 1995 Top Discovered At Fermilab

i) 10 years of top physics (Narrow Perspective)

Why is m_t so large? ($t\bar{t}$ condensation?)
What is m_t ? (Exotic top properties?)

$m_t = 174.3(5.1) \text{ GeV} \xrightarrow{2004} 178.0(4.3) \text{ GeV} \xrightarrow{2005} \frac{172.7(2.8) \text{ GeV}}{\text{Preliminary}}$

Can m_t go lower? higher?

$m_t - m_W$ connection: m_W (had. coll) = 80.454(59) GeV
 m_W (e^+e^-) = 80.412(42) GeV

$m_W^{\text{ave}} = 80.426(34) \text{ GeV}$

TeV Run II $\rightarrow \pm 25 \text{ MeV}$

$m_t \approx 173 \text{ GeV} \rightarrow m_W \leq 80.370$ in SM for $m_H \approx 114 \text{ GeV}$

Will m_W come down? Probably

ii) Higgs Mass $\propto G_H, m_2, m_t + m_W$ or $\sin^2 \theta_W(m_2) \rightarrow m_H$

$m_W = 80.426(34) \text{ GeV} \rightarrow m_H = 42_{-27}^{+47} \text{ GeV} < 135 \text{ GeV (95\%)}$

$\sin^2 \theta_W(m_2)_{\text{lept. MS}} = 0.23085(21) \rightarrow m_H = 52_{-24}^{+35} \text{ GeV} < 122 \text{ GeV (95\%)}$

**Higgs Right Around The Corner?
Passed?
New Physics?**

However $A_{FB}(Z \rightarrow b\bar{b}) \rightarrow \sin^2 \theta_W(m_2)_{\text{Had MS}} = 0.23186(27)$

implies $m_W = 80.261(47)$ **Inconsistent!**
(Indep. of m_t)

$m_H = 400_{-200}^{+280}$ $\lesssim 1 \text{ TeV (95\%)}$

Low energy $\sin^2 \theta_W$ measurements (\rightarrow susy GUTs) also favor heavy Higgs, but uncertainty is large

How do we resolve $\sin^2 \theta_W(m_2)_{\text{MS}}$: A_{LR} vs $A_{FB}(Z \rightarrow b\bar{b})$?

Giga Z Factory $\rightarrow \Delta \sin^2 \theta_W \sim \pm 0.00002$
(requires pol. e^+e^- beams at $\sqrt{s} = 91.196 \text{ GeV}$)

iii) Harbingers of Supersymmetry

- 1) Dark Matter (Neutralino?)
- 2) susy GUT Unification $M_x \sim 10^{16} \text{ GeV}$
- 3) Light Higgs Loop Prediction $m_H < 150 \text{ GeV}$

Muon Anomalous Magnetic Moment

E821 $a_{\mu}^{\text{exp}} = \frac{g_{\mu} - 2}{2} = 116592080(60) \times 10^{-11}$

E969 $\rightarrow \pm 25 \times 10^{-11}$ factor 2.5 better (Not Funded)

$$a_{\mu}^{\text{SM}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{Had.}}$$

$a_{\mu}^{\text{QED}} = 116584719(1) \times 10^{-11}$ 1-5 loops! (Kinoshita)

$a_{\mu}^{\text{EW}} = 154(1 \times 2) \times 10^{-11}$ 1+2 loops + leading 3 loop
Higgs

$a_{\mu}^{\text{Had.}} = 6956(53)_{e^+e^-} (35)_{\text{RC}} (35)_{\text{LBL}} \times 10^{-11}$ 2+3 loops, $e^+e^- \rightarrow \text{hadrons}$

$a_{\mu}^{\text{SM}} = 116591829(53)_{e^+e^-} (35)_{\text{RC}} (35)_{\text{LBL}} (3) \times 10^{-11}$



$\Delta a_{\mu} \equiv a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = 251(93) \times 10^{-11}$ e^+e^- data

$114(89) \times 10^{-11}$ $\leftarrow \tau \rightarrow \nu_{\tau} \pi^0 \pi^0$ data

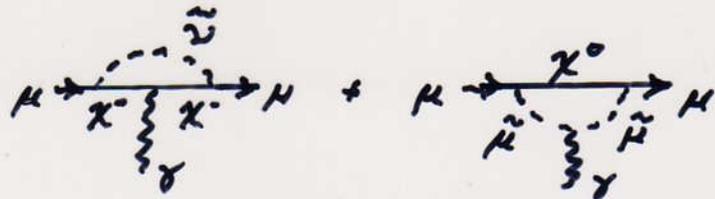
2.7 or 1.3 sigma deviation?

New $e^+e^- \rightarrow \tau$ data: Novosibirsk, Belle, BaBar... seems to reduce $e^+e^- \rightarrow \tau$ discrepancy

My Guess $\Delta a_{\mu} \rightarrow 200(85) \times 10^{-11}$ (2.4 sigma)
 only a Guess

Wait For Full Analysis

Supersymmetry:



$$a_\mu^{SUSY} \approx (\text{sign } \mu) \times 130 \times 10^{-11} \tan \beta \left(\frac{100 \text{ GeV}}{m_{SUSY}} \right)^2$$

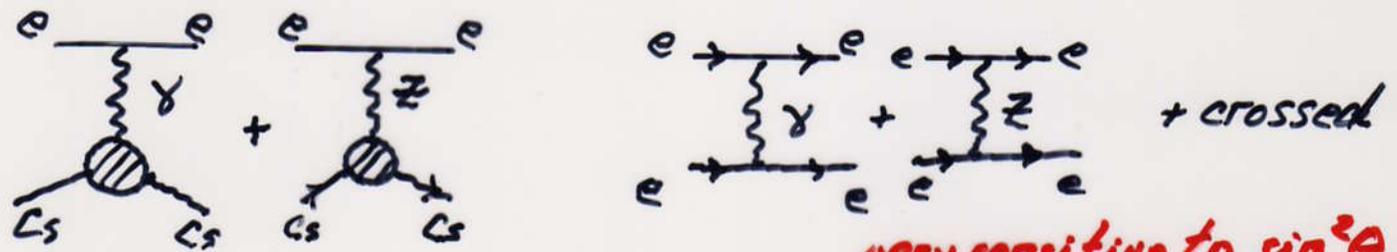
sign $\mu = +$ or $-$

$\tan \beta = \langle \phi_2 \rangle / \langle \phi_1 \rangle \approx 3-40$ (Enhancement)

Deviation $+200 \times 10^{-11} \rightarrow m_{SUSY} \approx 80 \sqrt{\tan \beta} \text{ GeV}$ *Right ballpark*

If SUSY found at LHC, $\Delta a_\mu \rightarrow \tan \beta$ value!

ii) Atomic P.V. + e^-e^- Scattering E158 at SLAC (A_{LR})



*very sensitive to $\sin^2 \theta_W$
 $\sim (1 - 4 \sin^2 \theta_W)$*

+ Radiative Corrections

Measure $\sin^2 \theta_W(Q^2 \approx 0)$ Low Energy

$\sin^2 \theta_W(Q^2)$ runs due to γ Z } opposite signs

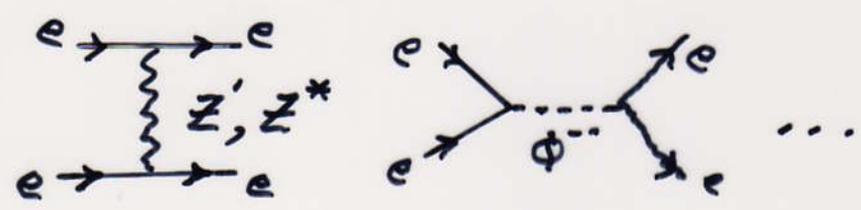
Expect: $\sin^2 \theta_W(0) = 1.03 \sin^2 \theta_W(m_Z)_{MS}$

Confirmed by E158 at 6 σ , $A_{LR}(e^-e^-) = 131(17) \times 10^{-9}!$

APV + Pol e^-e^- : good agreement with SM + running
do not confirm μN anomaly

Slightly high $\sin^2\theta_W(m_Z)$ favored but errors large
 $\Delta\sin^2\theta_W \approx \pm 0.0010$

New Physics?



Eg $m_{Z_\chi} > \underline{1 \text{ TeV}}$ e^-e^- } $SO(10)$ Bound
 $> 0.8 \text{ TeV}$ APV }

Other Interesting Constraints As Well

E15B $\rightarrow \sin^2\theta_W(m_Z)_{MS} = 0.2330(13) \rightarrow$ heavy Higgs

JLAB $A_{LR}(ep \rightarrow ep) \rightarrow \Delta\sin^2\theta_W(m_Z)_{MS} = \pm 0.0008$

126eV upgrade $A_{LR}(e^-e^- \rightarrow e^-e^-) \rightarrow \Delta\sin^2\theta_W(m_Z)_{MS} = \pm 0.0003$

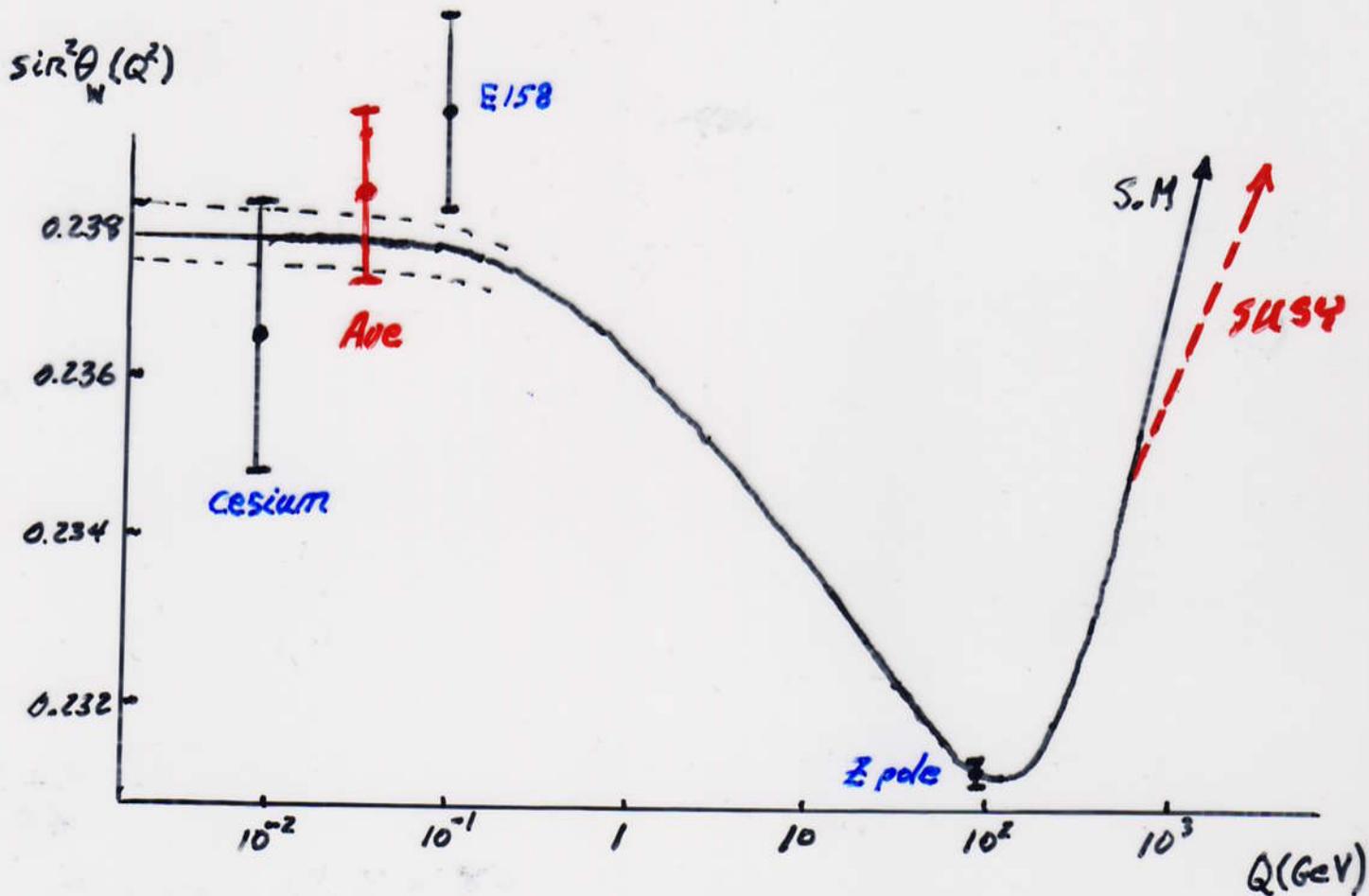
Competitive with Z pole
Must Do if Possible!

Fixed Target ILC $e^-e^- \rightarrow e^-e^-$ A_{LR} (K. Kumar)

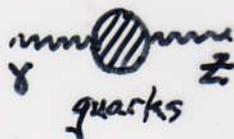
$\Delta\sin^2\theta_W(m_Z) = \pm 0.00006!$ Only e^- pol. needed

$E_e \approx 250 - 500 \text{ GeV}$ Fixed Target Program at ILC?

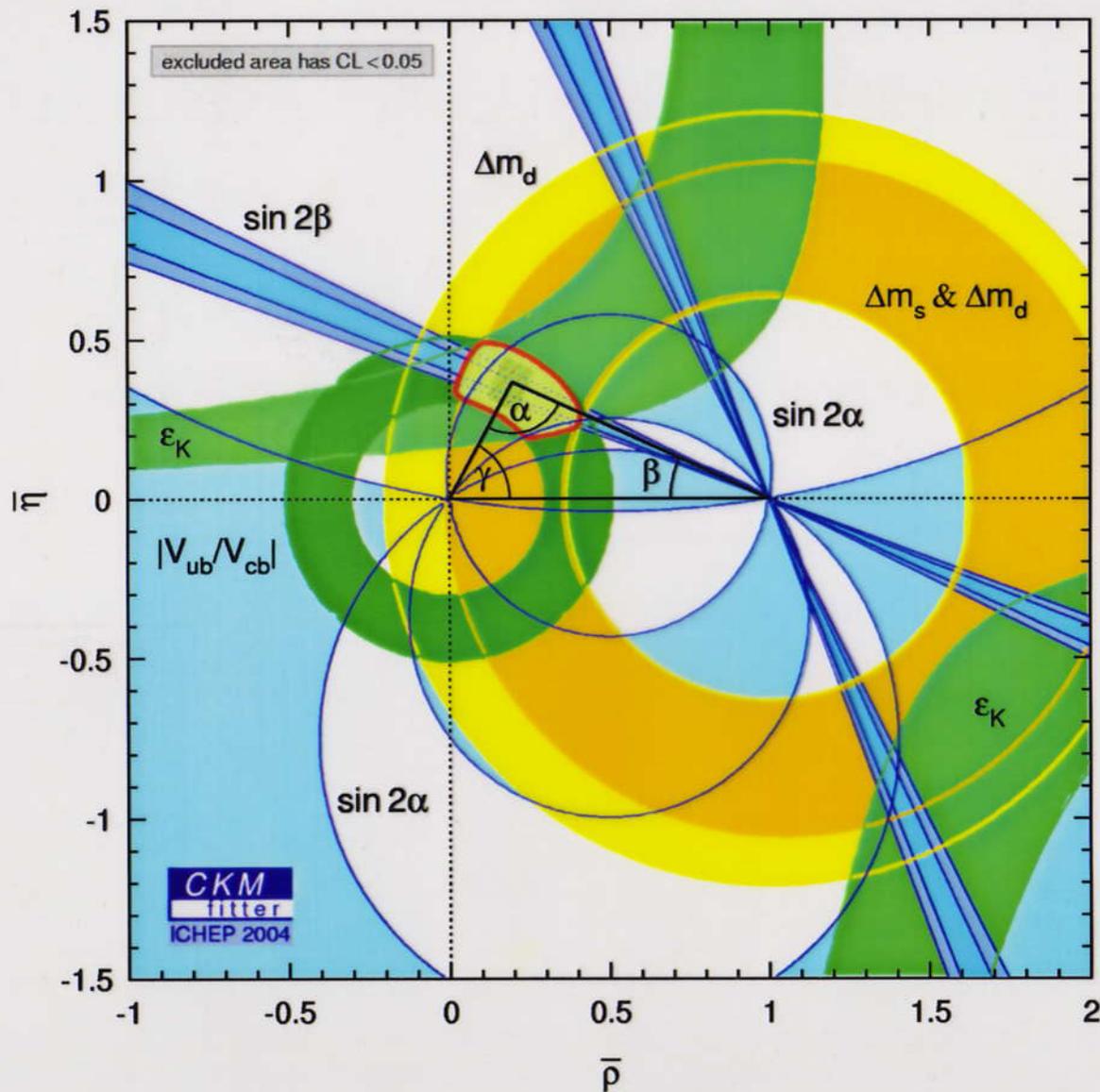
Running of $\sin^2 \theta_W(Q^2)$ ($\sim 6\sigma$ confirmation)



$$\sin^2 \theta_W(0) = 1.0301(25) \sin^2 \theta_W(m_Z)_{\overline{MS}}$$



Putting All Observables On The ρ - η Plane



Beautifully
consistent
overlap !

BUT !

The Kaon Revolution & V_{us}

- (2003) BNL (E865) $K^+ \rightarrow \pi^0 e^+ \nu_e$
- (2004) FNAL (KTeV) $K_L \rightarrow \pi^+ e \nu, \pi^+ \mu \nu$ All K_L BR Change
- CERN (NA48) $K_L \rightarrow K^+$
- Frascati (KLOE) K_L, K_S, K^{\pm}

All find 5-6% Increase in BR ($K \rightarrow \pi l \nu$)!

$$|V_{us}| = 0.2257(9) \left(\frac{0.961}{f_+(0)} \right)$$

$f_+(0) = 0.961(8)$ Leutwyler + Roos (1984)
Lattice Confirmation

Meanwhile V_{ud} Improvements Exp & Theory

$$|V_{ud}| = 0.97377(19)_{\text{Exp Nucl}} (19)_{\text{loops}}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992(5)_{\substack{V_{ud} (4) \\ K_{23} (8) \\ f_+(0) (8)}} \quad \text{Unitarity Good!}$$

(10)

Future Lattice $\rightarrow (7) \quad f_+(0) + f_K/f_\pi$

Possible Problems: χ^2 PT $\rightarrow f_+(0) = 0.974 \rightarrow |V_{us}| \approx 0.2227$

* Penning Trap β -decay Q Value
 \rightarrow lower V_{ud} (perhaps 0.9731)

We could find (1-2yr): $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9965(7)$ **50!**

It ain't over till it's over!

Nucleus	t_f (sec) (Savard et al.)	V_{ud}
^{10}C	3039.5 (47)	0.97381 (77)(15)(19)
^{14}O	3043.3 (19)	0.97368 (39)(15)(19)
^{26}Al	3036.8 (11)	0.97406 (23)(15)(19)
^{34}Cl	3050.0 (12)	0.97412 (26)(15)(19)
^{38}K	3051.1 (10)	0.97404 (26)(15)(19)
^{42}Sc	3046.8 (12)	0.97330 (32)(15)(19)
^{46}V	3050.7 (12)	* <u>0.97280 (34)(15)(19)</u>
^{50}Mn	3045.8 (16)	0.97367 (41)(15)(19)
^{54}Co	3048.4 (11)	0.97373 (40)(15)(19)

Ave 0.97377 (11)(15)(19)

Recent Change: ^{46}V

Q Value Change +2.2 keV
Penning Trap

$$t_f = 3045.5(22) \rightarrow 3050.7(12)$$

$$V_{ud} = \underline{0.97363(44)(15)(19)} \rightarrow \underline{0.97280(34)(15)(19)}$$

Major Shift!

Other Q Values Need Remasurement!

Big Problem?
(Major Revolution?)

BNL Intense Neutrino Beam → Homestake, WIPP, or Henderson

Zohreh Parsa



AGS 28 GeV protons, 1 MW beam (power achievable) +
500 kT Water Cerenkov detector, $5e7$ sec of running,
Conventional Horn based beam →

Zohreh Parsa
May 23, 2003

BNL Very Long Baseline Neutrino
Oscillations

BROOKHAVEN
NATIONAL LABORATORY

ii) Lepton Mixing + CP Violation

3 Generations: $m_1, m_2, m_3, \theta_{12}, \theta_{13}, \theta_{23}, \delta$

$$\theta_{23} \approx 45^\circ, \theta_{12} \approx 32^\circ, \theta_{13} \approx 13^\circ : \sin^2 2\theta_{13} \lesssim 0.2$$

How small is θ_{13} ? $0 \leq \delta < 360^\circ$

$$\Delta m_{21}^2 = m_2^2 - m_1^2 \approx 8.1 \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{32}^2| = |m_3^2 - m_1^2| \approx 2.2 \times 10^{-3} \text{ eV}^2 \quad (\text{sign?})$$

$$\left| \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \right| \approx \frac{1}{27} \quad \text{CP Experimentally accessible}$$

if $\sin^2 2\theta_{13} \approx 0.01 - 0.20$ (95% CL)

Ingredients: 1 MW proton beam \rightarrow WBB ν_μ (0.5 GeV - 5 GeV)
 500 kton H_2O detector (proton decay detector)
 $L \approx 1000 - 4000 \text{ km}$
 $T \approx 5 \times 10^7 \text{ sec}$

Measure: δ to $\pm 10 - 15^\circ$

Also sign Δm_{31}^2 , Δm_{31}^2 to $\pm 1\%$ Δm_{21}^2 to $\pm 5\%$

Precision θ_{23} + θ_{12}

Look for sterile ν , extra dim, dark energy

4. Outlook

Tevatron: $m_t, m_W, \text{Higgs}, Z'$, Surprises (Exciting)

B Factories: Rich Programs GP, Rare Decays \rightarrow Super B

K + μ Physics: CERN, PSI, JPARC (PRISM) $\rightarrow \mu^+ N \rightarrow e^- N$
(10^{-18})

* LHC - Higgs, SUSY, Extra Dim. (Spectacular)
(ILC)

neutron (SNS): $\tau_n, g_R, \text{edm.}$ (Dedicated Program)

Pol. e^- JLAB ep, $e\bar{e}$ (?)

ν osc. $\sin^2 2\theta_{13} \rightarrow 0.06$ MINOS, CERN, CHOOZ
 $\rightarrow 0.01$ Reactors, T2K, NOUR

Longer Term - Very Long Baseline Neutrino Osc.

BNL or FNAL \rightarrow DUSEL

or

CERN \rightarrow Furland

or

JPARC \rightarrow Korea

250-500 kton H_2O
(proton decay)
supernova ν
etc

Opportunities For Discovery Great!

But HEP in the USA may be going over a cliff

Big Problem ~ 2009